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CRASH BEHAVIORUR OF HELICOPTER FUEL TANK STRUCTURES

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Abstract

Object of the present work is the study, by means of experimental testing and numerical simulations, of the crashworthiness characteristics of an helicopter fuel tank.
A good design of fuel tanks is essential in preventing dangerous injuries in crash landings; most of those injuries are in fact caused by fire generated by fuel leakage after the impact. While good results have been obtained in reducing accelerations expert by passengers during impacts improving seats and restraints systems, extensive effort are still required in order to reduce fire hazard in crash landings.
Finite element codes are now available to better understand the dynamics involved in these phenomenon. For this reason a first activity has been conducted using experiments and simulations to deeply investigate the problems connected with the crashworthiness of fuel tank. This first phase was conducted on simple structures representative of real fuel tanks: size, materials and shapes were maintained comparable with those used in helicopters components. Finite element gave reliable results regarding the global behaviour of the structure and the movement of the fluid inside the tank. Problems are still present regarding the simulation of rivets used to joint the specimens.
After this first phase the second part of the work was faced with a real fuel tank extracted from an Agusta helicopter. Preliminary simulations were conducted to obtain indications on the results of the experimental test. Existing regulations ask for fuel systems crash resistance to be verified with static tests and a final drop test. The prescribed static tests are of arduous realisation mainly due to the difficulty of representing fluid dynamic loads acting on to the tank structure. The work is finally trying to propose a new kind of testing for helicopter tanks by means of dynamic tests similar to those prescribed for other aircraft structure (i.e. seats).

Introduction

In the last years several attempts have been made to improve aircraft and helicopter passenger safety during crash landing. The introduction of shock absorber mounted on the seats and deformable subfloor have allowed to obtain a better safety than in the past. In this moment dangerous injuries are caused mainly by three causes: human body high accelerations, i.e. cerebral damages, impacts against cockpit surfaces and injuries caused by fire or suffocation. While a good safety can be achieved for the two first problems (accelerations and impacts), with already experimented solutions, for the third problem we are far from the solution. Numerous studies, conducted since the '40, have revealed the very severe hazard associated with postcrash fire. Table 1 (Ref. 1) show that approximately 15 percent of the injuries and fatalities in Army and civilian helicopter accidents in the '60 and '70 were caused by fire. At the end of the '60 U.S. Army issued the first regulations (MIL-T-27422A) with the objective of eliminate postcrash fire in survivable accidents. Crashworthy fuel systems were developed obtaining very encouraging results (see Tab.2).

Tab. 1 - Fire hazard in helicopter accidents

	Injuries		Fatalities	
	Thermal	Non-Thermal	Thermal	Non-Thermal
U.S. Army Helicopters 1967-1968 100 Accidents 133 Postcrash Fires	64	1.297	95	159
U.S. Civilian Helicopt. 1974-1978 86 Accidents	13	174	18	42

Tab. 2 Safety Improvements due to CrashWorthy Fuel System

	Survivable		Non survivable	
Classification	W/O CWFS	With CWFS	W/O CWFS	With CWFS
Thermal Injuries	20	5	5	0
Non-Ther. Injuries	529	386	13	28
Thermal Fatalities	34	0	31	1
Non-Ther. Fatalities	120	44	229	85
Accidents	1160	1258	61	32
Postcrash Fire	43	16	42	18

Civil regulations concerning postcrash fire hazard are been developed only in the 1993 and presently to avoid fire after an emergency landing two methods are considered: chemical products added to fuel to avoid

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inflammable vapour productions and new fuel structure design to limit the risk of fuel leakage after impact.
This work starts from these considerations concerning an existing fuel system designed before the issue of actual regulations on fuel tank crash resistance. The first objective was to investigate and better understand the aspects involved in these phenomenon.

Preliminary Tests.

In a helicopter crash the fuel system, in standard design solutions, is one of the first part of the structure that is involved in energy absorbing mechanisms. For this reason the helicopter crashworthiness of fuel tanks is, if possible, a more delicate problem than for fixed wing structure. Problems related with the study and the simulation of this phenomenon are:

- presence of the fluid inside the tank that, during the first phase of the impact, develops high pressure on the walls of the tank,
- eventuality of loss of fuel that can be burst into flames causing injuries to the occupants,
- damage mechanisms of the structure that is usually built with riveted joints.

The contemporary presence of the above mentioned aspects produces a lot of difficulties in the study and numerical simulation on the problem. This work represented for us the first approach to this part of the crashworthiness and for this reason we decided to start with a first phase facing with simple structures representative of real fuel tanks.
This structures (fig 1) have been built by Agusta helicopters and are representative of the technology used in Agusta helicopters, with a dimension of 670x638x300 mm and an internal volume of 105 dm^3.

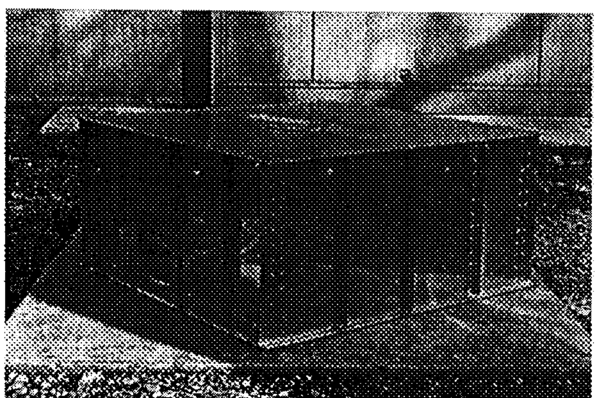


Fig 1 : Fuel tank specimen

Tests were conducted with water inside the tanks filling at 80% (100kg) and 50% (70 kg) of the volume. The structures impacted against a rigid surface with a speed of 12.1 m/s. The specimen have been fixed to a rigid frame used to install 4 accelerometers and 4 load cells on the edges (fig 2). These instrumentation has been chosen to avoid measures influenced by local conditions, for example strain gages placed on the vertical ribs.

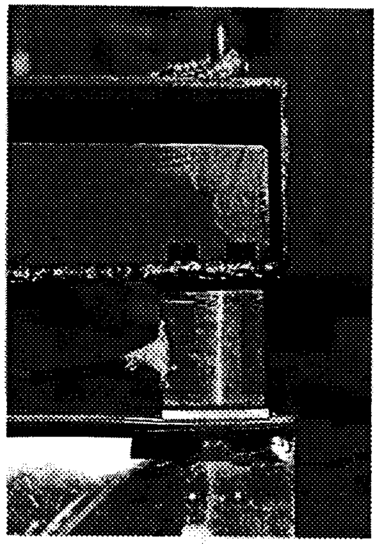


Fig 2: Load cell connected to the tank and rigid frame.

Just before the impact two photography cameras placed mutually perpendicularly have been used to measure the inclination of the specimen.
In the following figures the deformation obtained in one of the tests are reported.

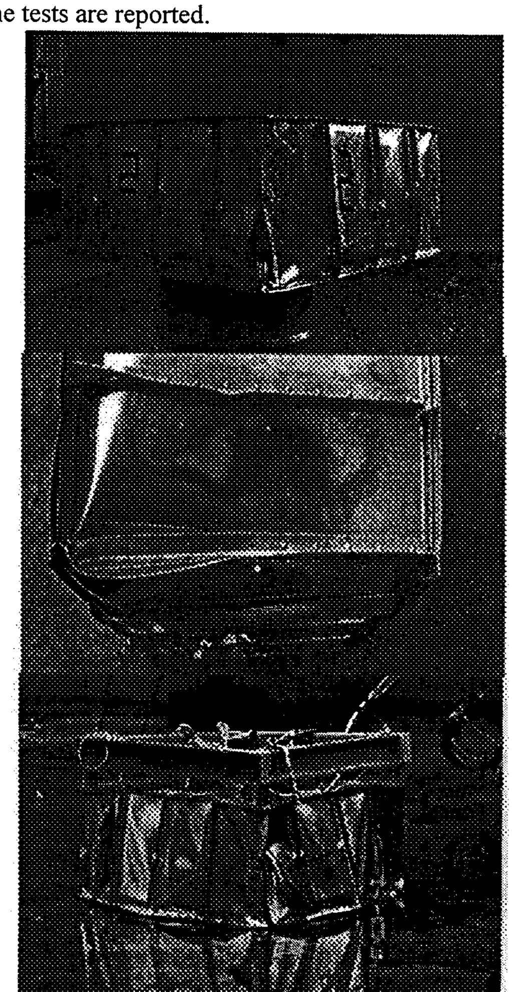


Fig 3: specimen after the test typical deformation.

6 tests have been conducted with 50% of water and 6 with 80 %. During the tests accelerations and loads have been recorded with a remote data acquisition system. In fig 4 the superimposition of the resultant acceleration time histories for the 50% impacts are reported.

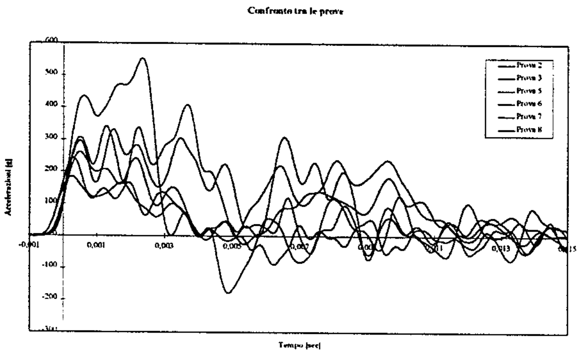


Fig 4. Resultant acceleration

In fig 5 photographs showing the position of the tank just before the impact are reported, with this technique the angle of impact has been evaluated in each test:

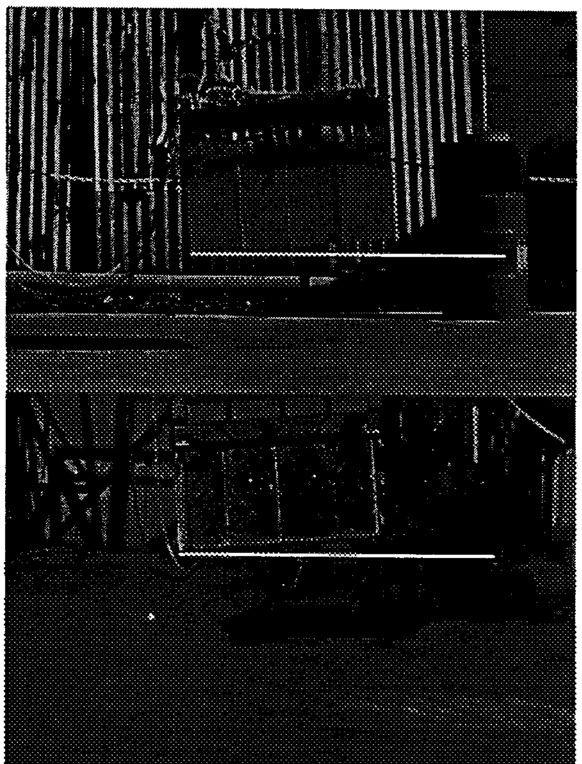


Fig 5.

Firsts experimental results can be here resumed:

- global deformations and failure modes in different tests are comparable even if different angles give completely different acceleration time histories,
- same level of energy causes failure of the structure and loss of water depending on the impact angle,
- all tests presented impact angles within the tolerance prescribed by the regulations (± 5° in the tests, ± 10° for the regulations) ,
- acceleration time histories give uniform plots in impacts with 0° angle,
- impact with angles different from 0° causes time shift of acceleration between different edges and bigger damage on the structure,
- impacts with comparable angles give similar results (fig 6, 7).

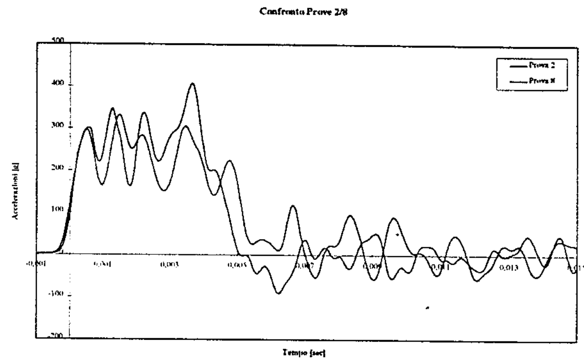


Fig 6: acceleration time history, 0° tests

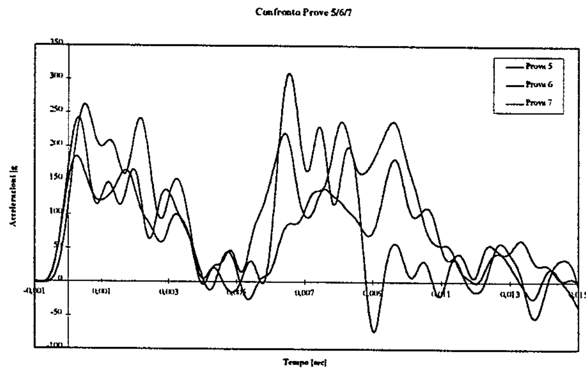


Fig 7: acceleration time histories, inclined impacts

Numerical simulations

Problems present during the simulation of this kind of impacts can be resumed:

- presence of fluid-structure interaction,
- requirement of modelling the flow of the fluid outside the broken structure (pass-fail criterion),
- damage mechanisms due to failure of rivets.

The numerical study of such a phenomena require the use of codes with good capabilities of representing transients with high non-linearities. Although the development of this type of code is relative new, some of them are extensively used and enough reliable.
The main difficulty for these simulations is the representation of the fluid inside the structure, this because the fluid does not fill the tank and therefore the movement of the water in the structure must be modeled.

This because the water during the crash exert dynamic pressure on the walls and his presence must be take into account to obtain reliable results (Ref. 4). The problem is the representation of two materials with behavior and constitutive laws completely different. A solution consist on representing the structural part of the tank through a lagrangian description and the fluid using an Eulerian description of the continuum (Ref. 5). Beside common lagrangian finite element codes some special codes based on a combined lagrangian-eulerian formulation has been developed. With this kind of approach no approximation is made on the constitutive model of the fluid and there isn't any problem caused by highly deformed mesh.

In the present paper are reported the results related to a numerical study conducted with the coupled code MSC-DYTRAN 4.0, based on a lagrangian-eulerian approach.

In this code the interaction between fluid and structure can be modeled using a complete Eulerian coupling or an ALE coupling. In the first case Lagrangian mesh is placed inside an Eulerian mesh containing the fluid. In each time step the intersection between the meshes is evaluated and this surface is used as a boundary for the fluid and as a loading pressure field for the structure.

In Ale coupling Lagrangian and Eulerian meshes have common boundary, that is during the impact the Eulerian mesh is deformed following the Lagrangian one. Main difference in the two algorithms is CPU time consumption. General coupling is more flexible but require a huge amount of CPU time to compute the interface being then not suitable in preliminary numerical simulations.

Ale coupling has been then used in these simulation to give reliable results in acceptable CPU time. One of the problems of Ale coupling is the requirements of closed interface surface between eluerian and lagrangian meshes. For this reason the flow of water outside the failed structure cannot be modeled and than the failure of the tank cannot be seen. To avoid this problem the models have been built using two lagrangian structures:

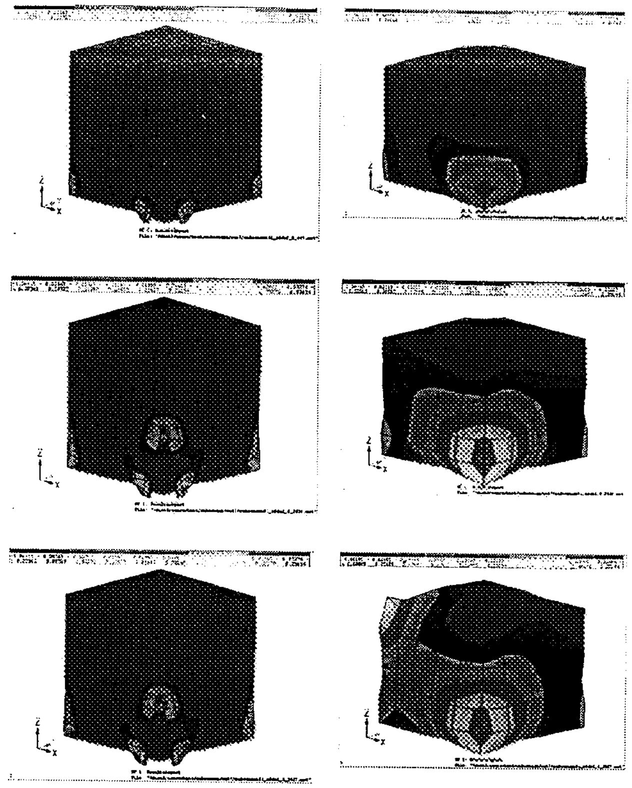
- the first is the real structure representing the tank,
- the second is a bag, not present in the real tank, used to contain the fluid, this bag is modeled with a material stiffness order of magnitude less than the material of the real structure.

With this expedient the simulation can describe the failure of the structure and the flow of water outside the tank. This technique has been set up using a simple model representing a cube filled with water that can flow from one edge (fig 8).

Two models have been then developed, the first to study the global behavior of the simulation, the second to have results comparable with the experiment also referring to the acceleration time histories.

The first model used 4008 shell elements for the structure, 3050 shells for the bag, 16200 brick elements for the fluid.

The second model used 10240 shell elements for the structure, 3050 shells for the bag, 16200 brick elements for the fluid.



Structure   Bag with water.

Fig 8

The material of the structure has been modeled with an elasto-plastic law with strain rate sensitivity, the fluid has been modeled with a polynomial pressure-density law. The rigid frame and the load cells have been modeled by means of elastic beams, the with an elastic material with Young modulus 1000 time less than the modulus of the aluminum.

The rivets have been modeled with two different techniques:

- the first is to use the element bjoints present in the code to describe bolts and rivets, the use of these elements should be simple but introduces a lot of instabilities in the code causing a tremendous reduction of the time step,
- in the second we used small beams where trimming area, inertia moments and shear resistance we were able to reproduce the different failure modes of joints, unfortunately this kind of model require a great development time.

This last technique has been used to model few joints in the lower part of the tank that could be damaged during the impact.

The lateral panels have been described as distinct structure to have the capability of representing the loss of fluid from an eventual failure.

In the following table the distribution of CPU time over different tasks is reported:

Phase	Cpu time s	% of total
Building the model	94.52	0.36
Contacts	3787.64	14.72
Lagrangian elements	8678.78	33.73
Lagrangian nodes	1711.19	6.65
Eulerian elements	8694.83	33.80
Eulerian nodes (ALE)	2628.45	10.21
Editing	128.51	0.50
Total	25724.33	100.00

In fig 9 and 10 the Eulerian and Lagrangian mesh of the detailed model are reported.

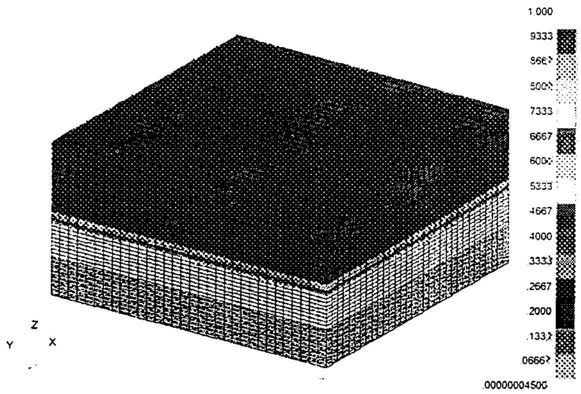


Fig 9 Eulerian mesh (white-water)

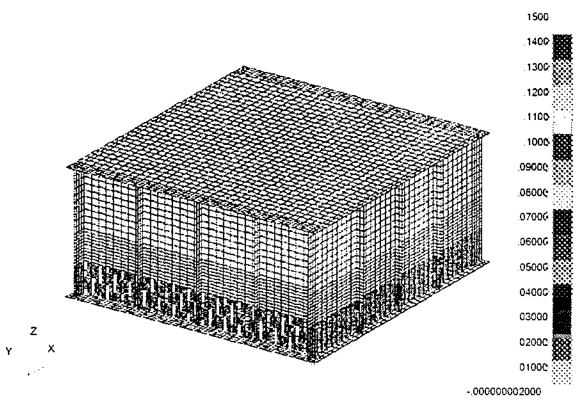
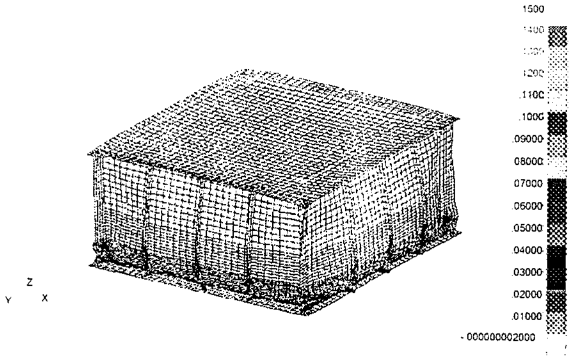


Fig 10: Lagrangian mesh

In fig 11 the deformation at the end of one simulation is reported as well as the pressure field in the lower part of the tank during the phenomen. This simulation refers to a 12 m/s impact with an angle of 2° in each direction.



Deformation at the end of the simulation.

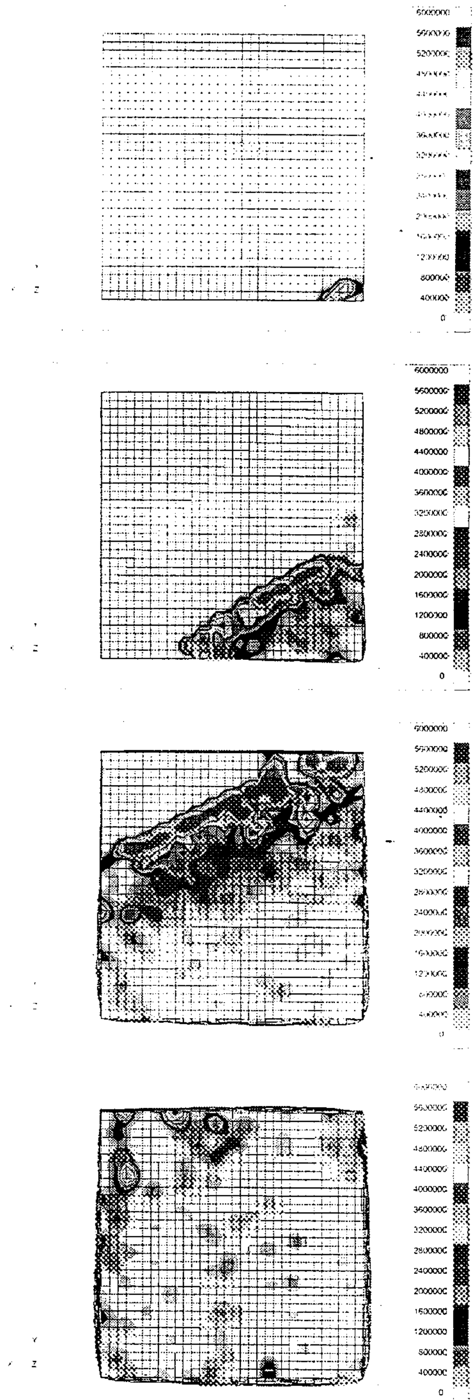


Fig 11: pressure field on the floor.

In fig 12 is reported the comparison between the simulation and the experiments that presented the impact angle described.

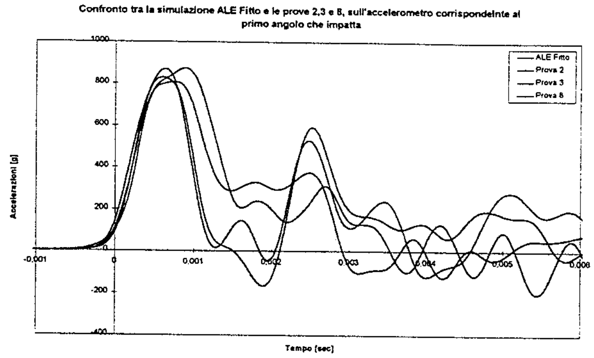


Fig 12: comparison between simulation an experiment

Conclusion of preliminary test.

The results can be highlighted in the following points:

- great influence on the results of the test is due to the angle of impact even if it is inside the tolerance given by the regulations,
- the same structure fail or pass the test (leakage of fluid) with small angle difference,
- the phenomenon can be represented using a finite element approach of the problem with good results,
- difficulties are still present in the representation of rivets,
- cpu time and size of the mesh are suitable also in preliminary simulations,

Real tank structure

The second part of the work faced with a real tank obtained from an Agusta helicopter. With this tank we tried to verify the compliance with the regulation regarding the crashworthiness of fuel tank.

Regulation Requirements and Limits

Regulations for civil helicopter (JAR 27-29, ref 2) require the fuel tank crash resistance to be verify by test at the following ultimate inertial load factor (in the case of fuel tank located above or behind the crew or passenger compartment) :

(i) Upward - 1.5g
(ii) Forward - 8g
(iii) Sideward - 2g
(iv) Downward - 4g

and by means of a final drop test from the height of 15.2 m. In each case the structure must represent a fuel tank with water to the 80% of the normal full capacity and at the end of the tests must retain its contents and exhibit no leakage.

Clearly the first four tests are not of easy solution due to the loads that must be simulated (hydrodynamic pressure on the tank walls). Considered as static tests they result inapplicable, while dynamic tests require information on acceleration pulses shape and duration. Besides, crash landings tests of other structural parts (i.e. seats) of the aircraft are already simulated by means of deceleration pulses obtained in especially designed crash test machines (Ref. 3).

Finally it seems then that the only way to find out the compliance with existing regulations is to setting up dynamic tests with specific deceleration pulses. At this point the problem is to find an appropriate pulse shape and to take in account for the shortness of such a dynamic test and for the strain rate sensitivity of the structural material.

Experimental Tests

Test Facility

The crash test facility in use by the Aerospace Department of the Politecnico of Milano belongs to the group of "deceleration sled facilities", that is to say that the sled after reaching a desired velocity, is decelerated according to a normalised pulse shape. The item is mounted on a sled running on 2 horizontal rails. The initial velocity is reached by means of a compressed air piston that launches the sled over a relatively long distance (4 meter). The compressed air system is capable to accelerate a 2000kg sled up to a velocity of 15 m/s. After the free run, the sled is decelerated by an oleo-pneumatic brake which provides the desired pulse shape and avoids the sled to move back. This facility is in use f mainly for seat tests according to TSO regulations.

Dynamic Tests

With the purpose of maintain almost the same structural stress, as in static tests described in the regulations, appropriate deceleration pulses have been set up. In particular deceleration pulses with safety factors if compared with standard regulations have been developed. This to take in account the strain rate sensitivity of the structural materials behavior and the shortness of the phenomenon.

The inertial load factors considered has been:

(i) Forward - 12g
(ii) Sideward - 4g

Owing to some difficulties due to leakage's from the tank locking cap in the vertical position, the tests with upward and downward inertial loads prescribed by regulation has not been carry out. While the upward test seems to be not significant (because of its low acceleration level), the

downward one, with the forward test, is particularly crucial and will be performed in the future activities.
The fuel tank was installed onto the sled with a structure representing the fuselage section near the tank itself. In particular has been represented the landing gear and the fuselage connections (Fig. 13).

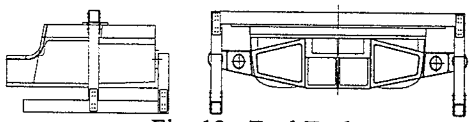


Fig. 13 - Fuel Tank

Even if is not required by the regulations the structure has been instrumented by means of 8 accelerometers to obtain information on the displacements of the walls of the structure to be compared with numerical simulations. The accelerometers has been set on that tank walls that are in contact with the fluid. The tests have been conducted filling the tank with water to the 80% of the normal full capacity.
Figures 14 and 15 depict the facility conditions related to the forward and sideward tests.

Fig. 14 - Foreward Test

Fig. 15 - Sideward Test

The pulse shape adopted was the most rectangular the facility system could realize (see Fig. 16,17).

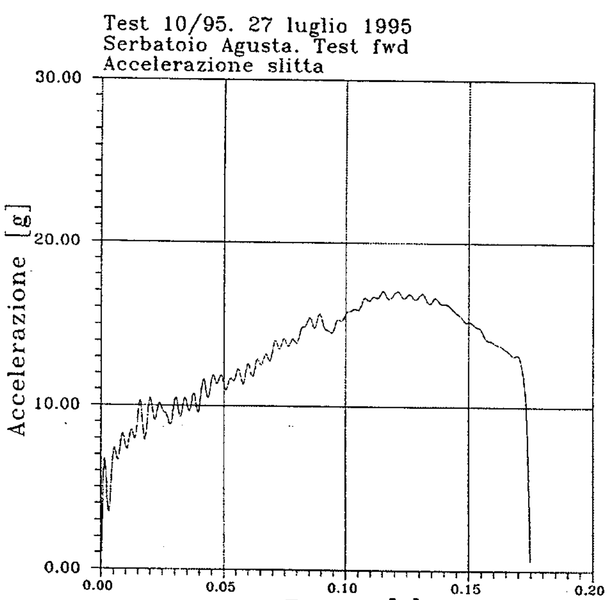


Fig. 16 - Forward Test Acceleration Pulse

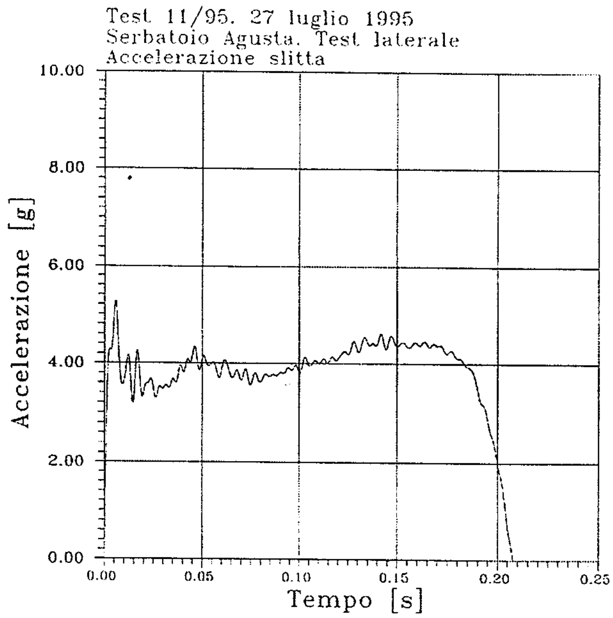


Fig. 17 - Sideward Test Acceleration Pulse

These dynamic tests have been followed by the final drop test from 15.2 m height. The tank has been winched with a jib crane by mean of a four point attachment and fast release hook (Fig. 18).

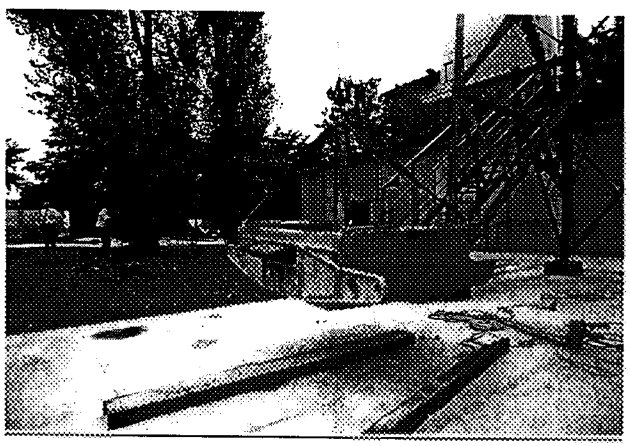


Fig. 18 - Fuel tank lifting

Results

Interesting results have been obtained from these tests conducted on a structure designed to not satisfy the Jar 29 regulations, and even if with minor modifications the structure will be able to pass the tests in the future.
In both dynamic tests there was no leakage's of water and no residual deformation of the structure was found. In particular a good behavior has been verified for the connections of the fuel tank to the helicopter structure. Figures 19 and 20 show the displacement on the upper and frontal panel in the forward acceleration test. In the sideward loading test no significant data on the

displacements has been possible to carry out (from the accelerometers signals) because of the position of the sensors and the low value of the acceleration.

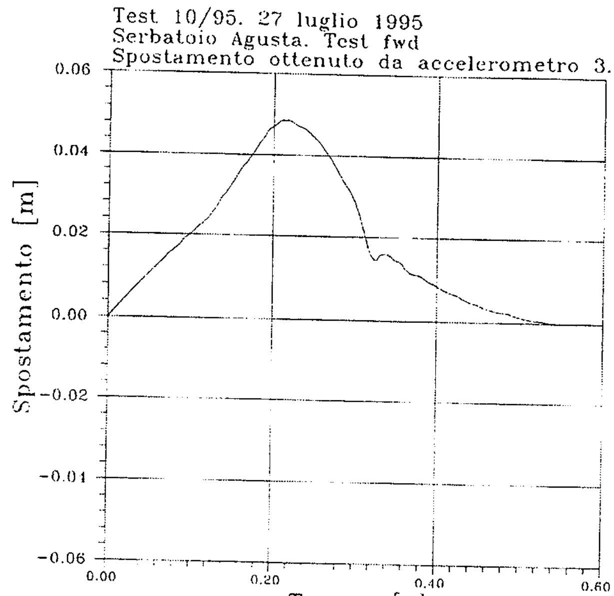


Fig. 19 - upper panel displacement

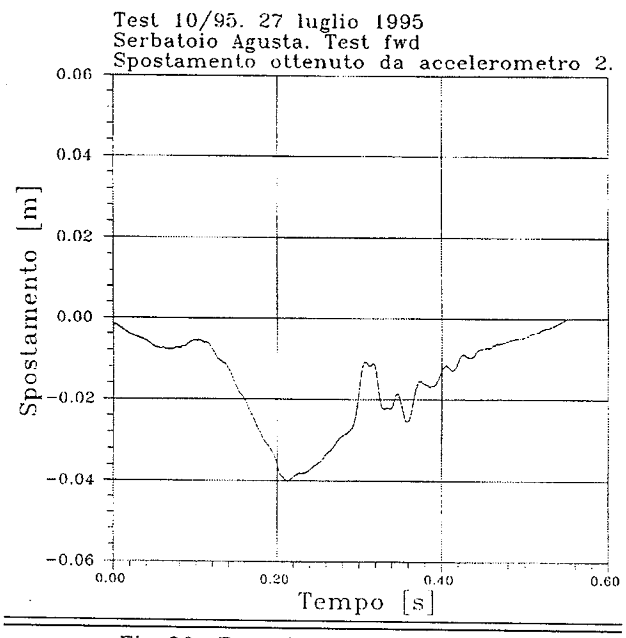


Fig. 20 - Frontal panel displacement

A less better behavior was verified in the drop test. During the drop test the tank has lightly changed his attitude going to impact near the landing gear connection zone. The structure attitude, anyway, has remained within a tolerance of 10° as prescribed by the regulation. Some leakage's had occurred due to the rupture of some valves in the lower part of the tank; anyway there was no tearing of the internal bladder.

In Fig. 21 are shown the fuel tank after the drop test. In this picture it could be seen that the main damage had occurred on the back of the tank, near the locking cap.

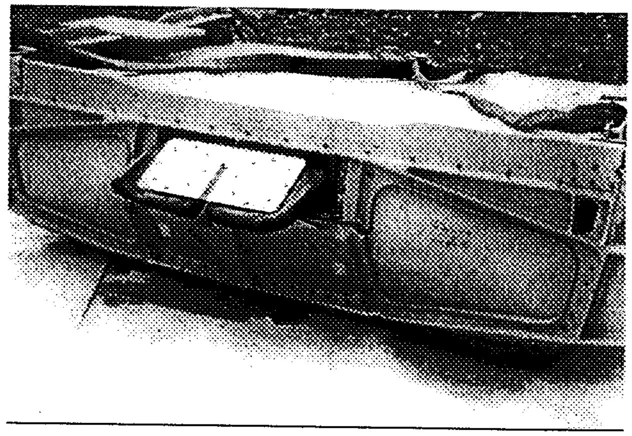


Fig. 21 - Fuel tank after the drop test

Numerical Simulation

Before the experimental activity a finite element numerical study of the phenomenon has been conducted to investigate if the procedure developed in the first phase of the work would have given reliable results if applied to a real structure

Model characteristics

The A109 fuel tank is mainly made of a sandwich structures realized of textile composite and alloy honeycomb. The facing materials are woven fabric of glass and kevlar fibers. With the purpose of better represent the behavior of such a material quite all the model was constructed by mean of solid elements covered by layered shell elements. The woven fabric has been represented by mean of a nonlinear bi-phase constitutive model with a damage fracturing law. The alloy honeycomb has been represented with a nonlinear bi-fase solid model; in such model the fiber phase is used to represent most of the axial cell elasticity and the highly non-linear cell crushing behavior, while the matrix phase is used to represent mainly the in-plane behavior.

The fluid inside the tank has been represented with solid elements characterized with a constitutive model based on the equation of state p=p(v).

The discretisation, shown in Fig. 22, consist of 1728 solid element, 2070 shell element and 159 beam element. In fig 23 is also shown the eulerian mesh.

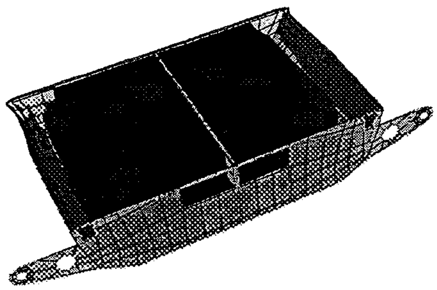


Fig. 22 - Fuel tank FE discretisation

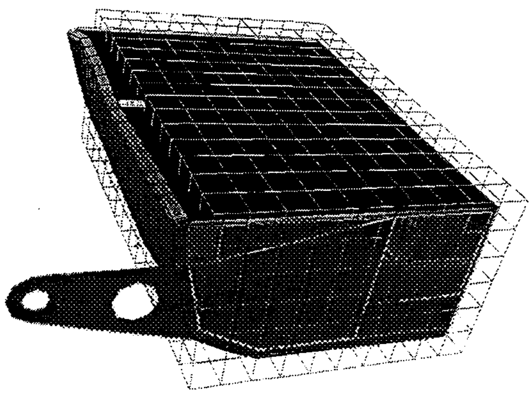


Fig. 23 - Fuel tank FE – Eulerian mesh

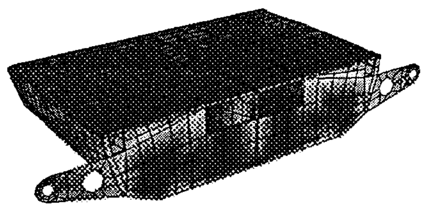
The test considered for the numerical analysis has been the drop test; the model, with an initial velocity of 17.27 m/s, corresponding to the height of 15.2m, impact on a rigid wall.

Results

These simulations have given interesting information on the phenomenon and indicated that the tank should have passed the test. Differences with the real experiment are mainly represented in the lower part of the structure where the presence of valves has been not modeled. These valves, as already mentioned, caused the leakage of water after the test. As could be seen, from Fig. 23 the deformation of the fluid seems well simulated. Obviously with this kind of representation there's no possibility of simulate any leakage.

The stress distributions at the impact (Fig. 23) confirm that the back panel of the tank is the part of the structure where possible ruptures could occur.

Finally in Fig. 23 and 25 are shown, respectively, rigid wall force magnitude and kinetic and internal energy.



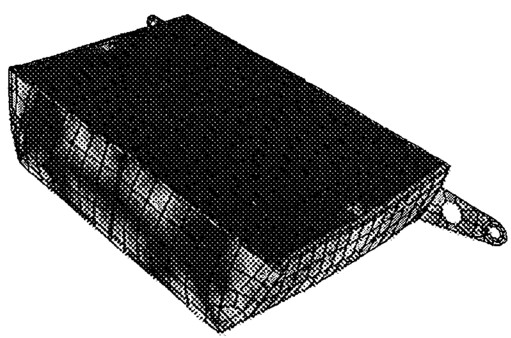


Fig 23 - Deformation contour

Conclusion

- Part of the actual regulations are not suitable for crash test.